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Sugarbeet Yield and Nitrogen Use Efficiency with Preplant Broadcast, Banded, or Point-Injected Nitrogen Application

W. Bart Stevens,* Alan D. Blaylock, James M. Krall, Bryan G. Hopkins, and Jason W. Ellsworth

ABSTRACT

Rising fertilizer costs and environmental concerns have heightened the need to improve N management in furrow-irrigated sugarbeet (*Beta vulgaris* L.) production. A study was conducted at two Wyoming locations to compare the effect of different preplant N placement strategies on yield, quality, and N use efficiency (NUE). Nitrogen was applied at rates from 0 to 358 kg ha^{-1} using three different placement strategies: broadcast and incorporated (BI), knife-banded (KB) 18 cm from the seed row, or point-injected (PI) 8 cm from the seed row. Placement had no consistent effect on root sucrose content. Point injection produced the greatest maximum predicted yield (Y_{MAX}) in five of six N responsive site-years with an average advantage of 603 and 975 kg ha^{-1} sucrose compared to BI and KB, respectively. The amount of N required for maximum sucrose yield ranged from about 10 to 100 kg N ha^{-1} less for PI than for other placement methods. For site-years where a response to N occurred, NUE was highest with PI, intermediate with KB (19% less than PI), and lowest with BI (28% less than PI). The advantage of PI, which placed N closer to the seed row than the other methods, was attributed to less leaching and greater uptake of N during early growth stages when the sugarbeet has little lateral root development. It was concluded that PI is an effective tool for maintaining high N concentration in the root zone for optimum early vegetative growth at lower N rates, thus improving NUE in sugarbeet production.

The sugarbeet industry provides an important economic enterprise for farmers in several temperate climate zones throughout the world, with total production of nearly 7 million ha in 2000 (Draycott, 2006). The importance of careful N management in sugarbeet production is well known. Insufficient N limits root yield while excessive amounts reduce root sucrose content and increase impurities that interfere with sucrose extraction. In addition to its agronomic impact, N management has taken on even more significance in recent years because of its economic and environmental impacts. Rising energy costs have caused the price of urea to roughly double since 2000 (ERS, 2005), and continued concern over NO_3–N contamination of water resources has caused reduction of N loss by leaching and runoff to remain a research and management priority (Di and Cameron, 2002; Spalding and Exner, 1993).

A substantial portion of sugarbeet production occurs in arid and semiarid climates, such as in the western USA, where supplemental irrigation is required. As with natural precipitation, irrigation can cause both surface runoff and excessive water flow through the soil profile, thus impacting N loss. Consequently, in irrigated areas N management decisions must consider the effect of irrigation practices to maximize NUE. In some irrigated sugarbeet production areas, including Wyoming, constant-flow furrow irrigation is common. This irrigation method provides several benefits, including low capital investment and a reduced risk of leaf diseases because irrigation water does not wet the foliage; however, water application efficiency is relatively low, ranging from 35 to 60% (Sterling and Neibling, 1994), depending on the level of management, soil type, and system design. A substantial portion of the inefficiency results from deep percolation, which in turn leaches NO_3–N. Meek et al. (1995) determined that NO_3–N moved on average 200 mm per irrigation in a furrow-irrigated Idaho silt loam soil. Artiola (1991) found that as much as 40% of NO_3–N was lost from the root zone, with one 300-mm irrigation on a clay loam soil amended with sludge. The risk of NO_3–N leaching is heightened further when dry soil conditions at seeding require irrigation to initiate germination. Silvertooth et al. (1992) used Br to evaluate NO_3–N leaching risk in furrow-irrigated cotton (*Gossypium hirsutum* L.) and found a high potential for leaching with early season irrigation events when there was little or no crop growth.

The propensity for preplant-applied N to be lost from the rooting zone is influenced by fertilizer placement, which is determined, at least in part, by the application method chosen. Broadcast and incorporated applications of dry ammonium nitrate (NH_4NO_3) or urea have been used extensively with sugarbeet because of the ease and speed with which the N can be applied. With broadcast application, fertilizer is distributed evenly across the field. This type of placement may lead to substantial NO_3–N leaching with subsequent irrigation because a portion of the fertilizer is located in the water furrow. Subsurface knife banding (KB) of urea-ammonium nitrate (UAN) or other liquid N solutions allows the placement of N in a band within the ridge. Though leaching potential is lower with KB, this application method causes high soil disturbance and requires a large

W.B. Stevens, USDA-ARS, Northern Plains Agricultural Research Lab., 1500 N. Central Ave., Sidney, MT 59270; A.D. Blaylock, Agrium Inc., Suite 1700, 4582 S. Ulster St., Denver, CO 80237; J.M. Krall, Univ. of Wyoming, Sust. Agric. Res. and Ext. Center, 2753 State Hwy. 157, Lingle, WY 82223; B.G. Hopkins, Dep. of Plant and Animal Sciences, Brigham Young Univ., Provo, UT 84602; and J.W. Ellsworth, Wilbur-Ellis Company, 150 Burlington St., Pasco, WA 99301. Mention of trade names, proprietary products, or specific equipment is intended for reader information only and constitutes neither a guarantee nor warranty by the ARS-USDA, nor does it imply approval of the product named to the exclusion of other products. Received 18 Dec. 2006. *Corresponding author (bart.stevens@ars.usda.gov).

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Abbreviations: BI, broadcast and incorporated; KB, knife-banded; NUE, nitrogen use efficiency; N_Y, N application rate at Y_{MAX}; PI, point-injected; UAN, urea-ammonium nitrate solution; Y_{MAX}, maximum predicted yield derived from N response function.

horsepower input. Baker et al. (1989) described a point injection (PI) implement for applying liquid fertilizers based on a spoke-wheel design. Among the advantages attributed to this method of N application are precise placement and minimal soil and plant disturbance (Timmons and Baker, 1992), while disadvantages include limited equipment availability and the high cost of spoke wheel units (Van Tassell et al., 1996). Nitrogen application with the PI applicator resembles KB, except that with PI the liquid fertilizer can be placed closer to the seed row and the distribution is discontinuous instead of an uninterrupted band.

Field research has confirmed that PI provides measurable benefits in some cropping systems. Blaylock and Cruse (1992) used ^{15}N to compare BI and PI of N in ridge-till corn (*Zea mays* L.) and found that PI increased corn yield and fertilizer N uptake, but they observed no difference when comparing injection near the crop row to injection midway between crop rows. In another study, fertilizer NUE was higher with PI than with surface-banded or KB application in no-till corn (Timmons and Baker, 1992). Vetsch and Randall (2000) showed PI improved no-till corn yield compared with broadcasting N following either corn or soybean [*Glycine max* (L.) Merr.]. Point injection has also been successfully adapted to reduced-tillage small grain production, where it provides the advantage of subsurface placement with minimal disturbance of the surface residue layer. Fertilizer N recovery in no-till winter wheat (*Triticum aestivum* L.) was greater with PI than with surface broadcast applications (Janzen et al., 1991). Schlegel et al. (2003) concluded that improved yield and a lower optimum N application rate made PI more profitable than BI in reduced tillage winter wheat.

With sugarbeet, N placement may be even more important than with other common crops owing to the importance of early season N availability to sugarbeet yield (Milford et al., 1985a, 1985b) combined with the limited lateral development of sugarbeet seedling roots (Weaver, 1926). Moreover, the high leaching potential under furrow irrigation further exacerbates the problem of efficiently meeting the early-season N requirement of sugarbeet. Consequently, the precision placement achieved using PI make this application method attractive as a means to improve NUE in furrow-irrigated sugarbeet production. We hypothesize that PI is a more effective method of applying N to sugarbeet than BI or KB. Our objectives were to compare (i) sugarbeet yield and sucrose concentration in response to different N placement methods, and (ii) the NUE of the different methods by determining the N response function and optimum N application rate for each.

MATERIALS AND METHODS

Site Description

Field studies were conducted at the University of Wyoming Research and Extension Centers at Powell and Torrington, WY. Conditions at these locations are representative of two of Wyoming's main sugarbeet producing areas. The Powell site (44°45′45″ N, 108°45′17″ W; 1326 m elevation) is located in the Bighorn Basin of NW Wyoming where the 30-yr mean annual precipitation and temperature are 185 mm and 7°C, respectively. The soil belongs to the Garland series (fine-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Typic Haplargids) typified locally by 0.5 to 1.0 m of moderately fine textured soil underlain by basalt sand, gravel, and cobbles. Because this soil was derived from alluvium, there was minor spatial variability in soil texture, which ranged from clay to sandy clay loam for the four experimental areas selected for this study. This variability occurred even though the four study areas (one for each year) were located in close proximity (<400 m) to each other. The Torrington site (42°04′40″ N, 104°12′45″ W; 1273 m elevation) is located in the Platte River Valley of SE Wyoming where the 30-yr mean annual precipitation and temperature are 352 mm and 9°C, respectively. The soil belongs to the Bayard series (coarse-loamy, mixed, superactive, mesic Torriorthentic Haplustolls) typified locally by very deep, well-drained soil within the North Platte River valley. Spatial variability of soil texture was less at this site than at Powell, with all three experimental areas (one for each year) having a sandy loam classification. Relevant chemical properties for each soil are shown in Table 1.

General Cultural Practices

Primary tillage at both sites was accomplished by moldboard plow in the fall. Secondary tillage at Powell consisted of two passes with a seedbed-preparation implement, known locally as a roller-harrow, and two passes with a leveling blade to ensure proper water flow in the irrigation furrows. Secondary tillage at Torrington was limited to a single pass with the roller-harrow. Phosphorus fertilizer in the form of triplesuperphosphate (0–22–0 N–P–K) was broadcast at rates determined from soil test results and University of Wyoming recommendations (Blaylock et al., 1996). Soil test levels of all other nutrients were sufficient according to University of Wyoming guidelines. All preplant fertilizer was incorporated to a depth of ≈10 cm by tillage. Sugarbeet followed barley (*Hordeum vulgare* L.) at Powell and corn at Torrington.

Sugarbeet seed (cv. HM R2 at Powell; cv. Monohikari at Torrington) was planted at a depth of 25 mm in mid-April for all site-years. Seed was planted in rows spaced 56 cm apart at Powell and 76 cm apart at Torrington. Target seed spacing was 12.5 cm at Powell and 10 cm at Torrington. Preplant herbicides and insecticide were applied and incorporated during the planting operation according to recommendations at the time the study was implemented.

Dry soil conditions at Powell required that plots be irrigated immediately after planting in all years to initiate seed germina-

Table 1. Soil chemical properties for experimental areas at Powell and Torrington, WY.

Soil property†	Year 1990	1991	1992	1993
	Powell			
Organic matter, g kg^{-1}	11	15	12	16
pH	7.6	7.8	7.8	7.8
NO_3–N, 0–30 cm, mg kg^{-1}	6	9	8	7
NO_3–N, 30–120 cm, mg kg^{-1}	0	1	2	2
	Torrington			
Organic Matter, g kg^{-1}	NA	14	19	16
pH	NA	8.0	7.6	7.7
NO_3–N, 0–30 cm, mg kg^{-1}	NA	9	4	8
NO_3–N, 30–120 cm, mg kg^{-1}	NA	11	11	2

† Organic matter by $K_2Cr_2O_7$ oxidation; pH by saturated paste; NO_3–N by colorimetric flow-injection analysis of a KCl extract; sample depth was 15 cm except where otherwise indicated.

tion and to fill the soil profile with moisture. Soil moisture at planting was sufficient at Torrington to germinate seeds without irrigation. Subsequent irrigations were performed at both sites to ensure that soil moisture was not limiting. Water was applied using a constant-flow furrow system at Powell with every other furrow receiving water. A self-propelled linear sprinkler system was used to irrigate the research area at Torrington in 1991, but a furrow irrigation system similar to the one at Powell was used in 1992 and 1993.

Postemergence weed control consisted of three applications of phenmedipham (3-methoxycarbonylaminophenyl N-3-methylphenylcarbamate) + desmedipham (ethyl m-hydroxycarbanilate carbanilate) at 5- to 7-d intervals beginning at the cotyledon growth stage. Application rates varied from 0.28 to 1.12 kg a.i. ha^{-1} depending on crop growth stage. When seedling emergence was complete in early June, plots were manually thinned to uniform populations varying by year and location from 66,700 to 84,000 plants ha^{-1}.

Experimental Methods

Experimental units were assigned using a randomized complete-block design. The dimensions of each experimental unit were 3.4 × 18.3 m at Powell and 3.0 × 18.3 m at Torrington. Treatments were replicated four times and consisted of a control (no N applied) and a factorial combination of N application rates and methods. Nitrogen placement at Torrington in all years and at Powell in 1990 consisted of PI using a spoke-wheel injector and BI. Placement treatments at Powell in 1991 through 1993 consisted of BI, KB, and PI.

Broadcast N was applied by hand just before planting as NH_4NO_3 then incorporated by tillage to a depth of 10 cm. Urea-ammonium nitrate solution (32% N) was utilized for KB and PI treatments, which were applied immediately following planting so as to achieve accurate placement with respect to the seed row. For PI treatments, a six-row spoke-wheel applicator injected UAN in a discontinuous band positioned 8 cm to the side of the seed row with injection points 20 cm apart and ≈8 cm below the soil surface. For KB treatments, a six-row backswept-knife applicator placed a continuous fertilizer band ≈8 cm below the soil surface and 18 cm to the side of the seed row. Where furrow irrigation was employed, injected N was placed on the nonirrigated side of the seed row (irrigation water was applied every other furrow) with both PI and KB. Nitrogen application rates (Table 2) for each site-year were selected based on expected yield goal and soil test NO_3–N. Adjustments to N application rates were made from year to year in an effort to best characterize the N response based on the previous year's results.

Root samples were harvested in late September or early October by hand-digging and topping 3 m of row from the center of each plot. Samples from the Powell site were weighed and analyzed for sucrose content by Western Sugar Company (currently Western Sugar Cooperative) and those from the Torrington site were processed by Holly Sugar Company. The Western Sugar Company analysis included brie impurities from which sugar-loss-to-molasses was calculated. Mention of sucrose yield refers to recoverable sucrose yield (sucrose yield minus loss-to-molasses) at Powell and sucrose yield at Torrington without correction for loss-to-molasses.

Table 2. Amounts of N applied to sugarbeet in each of the 4 yr of a N placement study conducted at Powell and Torrington, WY. Nitrogen was broadcast and incorporated, knife-banded (18 cm from row), or point-injected (8 cm from row) just before (broadcast) or just following (injected) planting.

Year	N applied: Powell	N applied: Torrington
	kg ha^{-1}	
1990	0, 67, 134, 201, 268, 335	NA
1991	0, 90, 179, 269, 358	0, 56, 112, 168
1992	0, 67, 134, 201, 268	0, 56, 112, 168
1993	0, 67, 134, 201, 268	0, 90, 179, 269

Statistical Analysis and NUE Calculation

Statistical analysis of data was performed by using ANOVA and general linear model procedures (SAS Institute, 2003). Mention of statistical significance refers to a probability level of 95% unless otherwise stated. For site-years with significant sucrose yield response to N rate, quadratic or quadratic-response-and-plateau models were fit to N rate means. Quadratic response models were estimated using the general linear models procedure. Quadratic-response-and-plateau models were estimated by using a nonlinear models procedure (SAS PROC NLIN). Predicted maximum sucrose yield (Y_{MAX}) and N rate at Y_{MAX} (N_Y) were calculated from the mathematical models by setting the first derivative of the quadratic function equal to zero (Gomez and Gomez, 1984).

The calculation of NUE was after Moll et al. (1982), who defined NUE for grain crops as the amount of grain produced per unit of available soil N. Sucrose production (i.e., sucrose yield) was substituted for grain production in this definition and NUE was calculated by dividing Y_{MAX} by total available N (N_Y + preplant soil N + mineralized N). Preplant soil N (kg ha^{-1}) was determined by multiplying the preplant soil NO_3–N concentration in Table 1 by 4.48 (common multiplication factor converting nutrient values from a weight to a volume basis) for each 30-cm depth increment. Seasonal N mineralization was estimated to be 20 kg N ha^{-1} for each 10 g kg^{-1} of soil organic matter (Blaylock et al., 1996).

RESULTS AND DISCUSSION

Root Yield

Increasing N application rate tended to increase root yield in all years at both Powell (Fig. 1) and Torrington (Fig. 2). The root yield response was greatest at Powell in 1993 (Fig. 1d); was moderate at Powell in 1990, 1991, and 1992 (Fig. 1a–1c); and was least at Torrington in 1991, 1992, and 1993 (Fig. 2a–2c). Statistical analysis confirmed these observations as N application rate significantly affected root yield in all years at Powell and in 1993 at Torrington (Table 3). The low response to applied N at Torrington in 1991 and 1992 was likely due to relatively high levels of residual NO_3–N in the lower soil profile. The NO_3–N concentration in the 30- to 120-cm depth was 11 mg kg^{-1} for these two site-years and 2 mg kg^{-1} or less in all other cases (Table 1), for a difference of ≈125 kg N ha^{-1}. Root yield with no applied N was consistently high at Torrington, indicating that nonfertilizer N sources contributed substantially to plant growth and thus limited root yield response to fertilizer N at that location.

Placement of fertilizer 8 cm from the row using PI produced greater root yield than with either BI or KB at Powell in 1992 ($P < 0.10$) and 1993 (Table 3). The interaction of N rate and placement was not significant in any year. At Powell in 1992, root yield with PI was greater than with BI, but differences between PI and KB and BI and KB were not significant (Table 4). In 1993, BI and

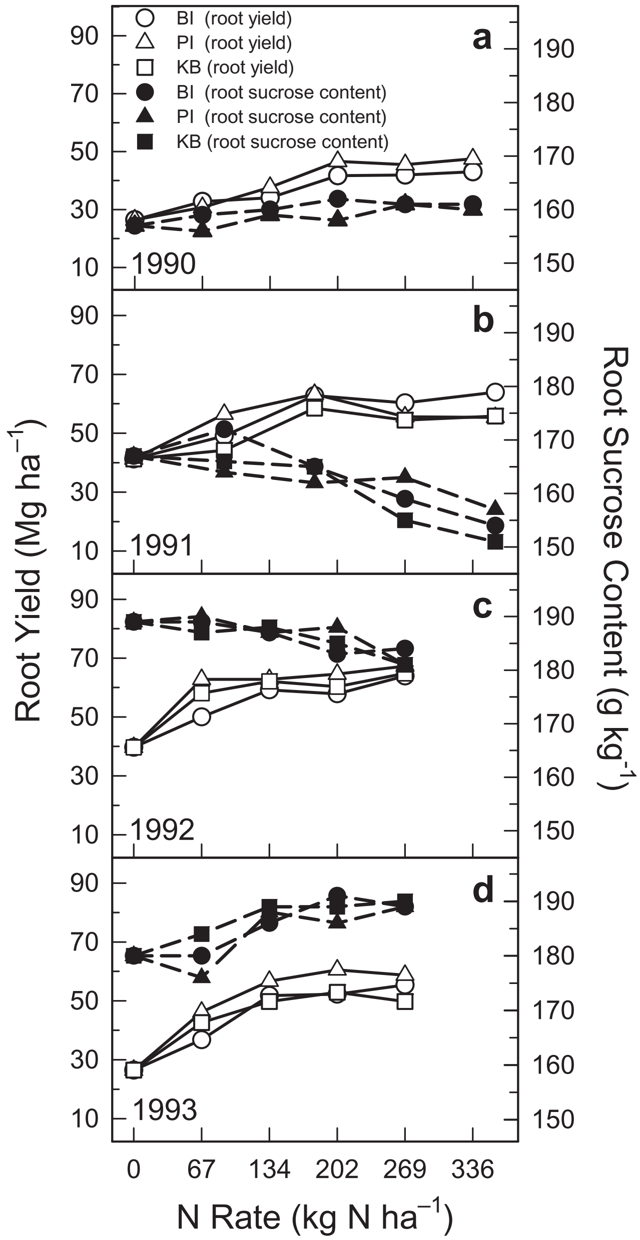

Fig. 1. Root yield and root sucrose content of sugarbeet grown at Powell, WY, with different amounts of N fertilizer and three preplant application methods [broadcast and incorporated (BI), point-injected (PI), or knife-banded (KB)]. Root yield data points (open symbols and solid lines) are read on the left axis while root sucrose content data points (solid symbols and dashed lines) are read on the right axis.

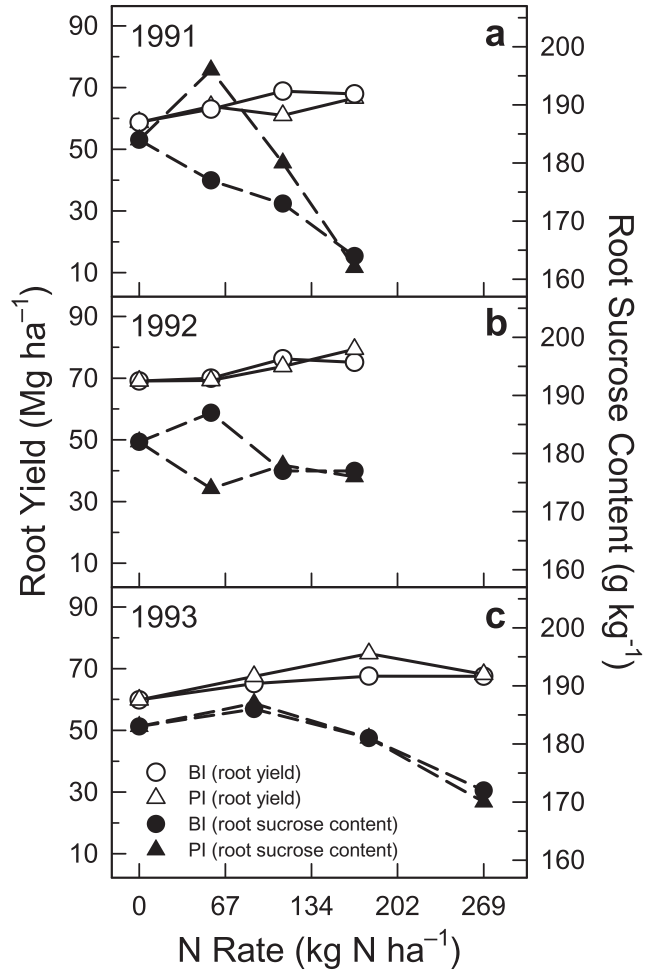

Fig. 2. Root yield and root sucrose content of sugarbeet grown at Torrington, WY, with different amounts of N fertilizer and two preplant application methods [broadcast and incorporated (BI), or point-injected (PI)]. Root yield data points (open symbols and solid lines) are read on the left axis while root sucrose content data points (solid symbols and dashed lines) are read on the right axis.

KB produced similar root yields, while with PI root yield was significantly greater than with both BI and KB. Averaged over all seven site-years, PI produced 61.1 Mg ha^{-1} in root yield, which was 2.5 Mg ha^{-1} greater than with BI (58.6 Mg ha^{-1}). Over the three site-years for which KB was included, BI, PI, and KB averaged 54.9, 59.2 and 54.2 Mg ha^{-1}, respectively.

Root Sucrose Content

Increasing N application rate tended to decrease root sucrose content in 1991 and 1992 at Powell (Fig. 1b and 1c) and in all years at Torrington (Fig. 2), while root sucrose content increased with increasing N rate at Powell in 1993 (Fig. 1d). The N rate effect was statistically significant for all site-years except for Powell-1990 and Torrington-1992 (Table 3). Root sucrose content tended to decline more sharply with increasing N rate at Torrington than at Powell (compare Fig. 1 and 2). The increase in root sucrose content with increasing N application rate at Powell in 1993 contradicts the results of most sugarbeet N studies (e.g., Carter and Traveller, 1981). This unexpected response was likely due to an early hard freeze in late August that terminated growth of sugarbeet in low N-rate plots. Limited N availability with these low N application rates resulted in sparse canopy cover, while sugarbeet treated with high N rates had substantial leaf area and were relatively unaffected by the freeze. By the time sugarbeet roots were harvested in late September, plants that received low amounts of N had begun producing new leaves. This leaf regrowth probably caused remobilization and use of stored sucrose, thus decreasing root sucrose content.

Table 3. Analysis of variance tests of significance for the response of sugarbeet root yield, root sucrose content, and sucrose yield to N application rate (N Rate) and N fertilizer placement method (Placement) at Powell and Torrington, WY.

	Powell				Torrington		
ANOVA source	1990	1991	1992	1993	1991	1992	1993
Root yield							
N Rate (R)	**	*	**	**	ns†	ns	*
Placement (P)	ns	ns	‡	**	ns	ns	ns
R × P	ns	ns	ns	ns	ns	ns	ns
Root sucrose content							
R	ns	**	**	**	**	ns	**
P	ns	ns	ns	ns	*	ns	ns
R × P	ns	ns	*	ns	*	*	ns
Sucrose yield							
R	**	**	‡	**	*	ns	**
P	‡	ns	*	**	ns	ns	ns
R × P	ns	ns	ns	ns	*	*	*

* Significant at the $P \leq 0.05$ level.
** Significant at the $P \leq 0.01$ level.
† ns, not significant.
‡ Significant at the $P \leq 0.10$ level.

Root yield (Table 4) and root sucrose response to N rate (Fig. 1) were lower for Powell-1990 than for other site-years. This may be attributed to unusually cool and wet spring weather conditions in 1990. The average temperature in May 1990 was 2.3°C lower than the 22-yr average, while the average for the other 3 yr was only 0.2°C lower than the long-term average. April and May precipitation for 1990 was 80 mm, compared with 44 mm for 1991 to 1993 (22-yr average is 49 mm). The cooler temperatures likely slowed early season metabolism and growth, thus reducing yield potential. The unusually high precipitation may also have leached some of the fertilizer N below the root zone, lessening the effect of N rate on root sucrose content.

Weather may have also been a factor in the strong response of root yield to N rate for Powell-1993 (Fig. 1d). The amount of precipitation from June to September of 1993 was 177 mm compared with the 22-yr average of 88 mm. This unusually high mid- to late-season precipitation may have caused above-average N loss, thus enhancing the response to N fertilizer.

Root sucrose content was generally unaffected by N placement (Table 4; Fig. 1, 2). This finding was somewhat surprising, as one might expect sucrose content to decrease as N uptake is improved. One possible explanation for this observation is that with PI, N is placed close to the plant creating a zone of high N concentration that is immediately accessible to the roots, thus allowing more N to be taken up early in the growing season than with BI or KB. Greater early season N uptake has been reported to increase yield potential and would also be expected to reduce the amount of N remaining in the soil later in the growing season when it can negatively affect root quality (Anderson et al., 1972). Carter et al. (1975) also reported that early season N nutrition affects root sucrose content at harvest. Therefore, although N uptake is improved by precision placement, root quality is not necessarily reduced.

The interaction between N application rate and fertilizer placement was significant for root sucrose content in three of the seven site-years (Table 3). At the Torrington location, the interaction is characterized by unexpectedly high values at the 67 kg-ha^{-1} application rate for PI and BI in 1991 (Fig. 2a) and 1992 (Fig. 2b), respectively. At Powell in 1992, the interaction is less clear because of the small differences among treatment means, but it appears to occur with the higher N application rates (Fig. 1c). Because of these inconsistencies, there is no obvious interpretation of the interactions.

Sucrose Yield

Management practices may have varying and opposing effects on sugarbeet yield and quality parameters.

Table 4. Sugarbeet root yield, root sucrose content, and sucrose yield as affected by N fertilizer placement at Powell and Torrington, WY. The data presented are placement effect means (i.e., average of all N application rates, excluding the check). Check (no N applied) means are presented for reference.

	Powell				Torrington		
Placement†	1990	1991	1992	1993	1991	1992	1993
				Root yield‡			
				Mg ha^{-1}			
BI	38.5 a	58.0 a	57.6 b	49.1 b	66.5 a	73.7 a	66.8 a
PI	42.3 a	57.6 a	64.5 a	55.6 a	63.8 a	74.1 a	70.1 a
KB	–	52.9 a	61.2 ab	48.6 b	–	–	–
Check	26.4	41.2	39.6	26.4	58.7	69.0	59.8
				Root sucrose content‡			
				g kg^{-1}			
BI	160 a	163 a	186 a	187 a	172 b	180 a	180 a
PI	159 a	161 a	187 a	185 a	179 a	176 a	179 a
KB	–	159 a	185 a	188 a	–	–	–
Check	157	167	189	180	184	182	183
				Sucrose yield‡			
				kg ha^{-1}			
BI	5981 b	8792 a	10315 b	8859 b	11390 a	13227 a	12309 a
PI	6350 a	8635 a	11581 a	9912 a	11390 a	13037 a	13328 a
KB	–	7773 a	10909 b	8837 b	–	–	–
Check	3991	6505	7269	4659	10789	12555	10942

† BI, broadcast and incorporated; KB, knife-banded; PI, point-injected.
‡ Means in a column followed by the same letter are not significantly different ($P < 0.10$).

Consequently, sugarbeet studies involving alternative practices should evaluate the combined response of yield and quality to management changes. The integration of these two yield components into one response is accomplished by calculating sucrose yield, which is the product of root yield (kg ha^{-1}) and root sucrose content (kg kg^{-1}). Sucrose yield is typically adjusted based on the amount of impurities in the root, which interfere with sugar refinement.

Sucrose yield response (Fig. 3) resembled root yield response (Fig. 1 and 2) in most cases. The N-rate effect was significant most years, while the placement effect was significant for two of seven site-years with an additional site-year (Powell-1990) exhibiting a response significant at the 0.10 probability level (Table 3). Placement main effects were significant in the two site-years (Powell-1992 and Powell-1993) with the greatest N response. Because the effect of N rate on root sucrose content was generally modest, root yield was the major determinant of sucrose yield. Comparisons among placement means show that PI resulted in greater sucrose yield than the other placement methods in site-years where the effect was significant (Table 4). Averaged over all site-years, PI yielded 480 kg ha^{-1} more sucrose than BI. Averaged over three site-years (Powell-1991, Powell-1992, and Powell-1993), PI produced 720 kg ha^{-1} more sucrose than BI and 870 kg ha^{-1} more than KB.

Nitrogen Use Efficiency

The influence of placement on NUE can be evaluated by determining the optimum N application rate for each placement method. Nitrogen-response curves for sucrose yield are shown in Fig. 3 with corresponding functions described in Table 5. The Torrington-1992 site-year is not included because the N-rate effect was not significant (Table 3). The derived functions described the sucrose yield responses very well (R^2 = 0.936–0.998) for four site-years (Powell-1990, Powell-1992, Powell-1993, and Torrington-1993) and well to moderately well (R^2 = 0.478–0.895) for the other two (Table 5). Sucrose yield response to N was quadratic for four site-years, but was best described using a quadratic-response-and-plateau model at Powell in 1990 and 1992 (Fig. 3 and Table 5). It is not surprising that four of six site-years produced a quadratic response since strongly declining root sucrose content dominates the sucrose yield function at the high N application rates. At the two site-years where sucrose yield reached a plateau, the root sucrose content response to N rate was weak (Fig. 1a, 1c).

A visual inspection of the response curves suggests that PI generally produced greater yield with less N than did the other two application methods, supporting the hypothesis the PI enhances NUE. This observation is confirmed by Y_{MAX} and N_Y values (Table 6). Point injection produced the greatest Y_{MAX} in five of six site-years, with an average advantage of 603 and 975 kg ha^{-1} sucrose compared with BI and KB, respectively. Also, N_Y was least for PI in all but one case. The exception was at Powell in 1993, when the N_Y was 16 kg ha^{-1} less for KB than for PI. While KB required less N to maximize yield in this one case, it was less productive, resulting in a

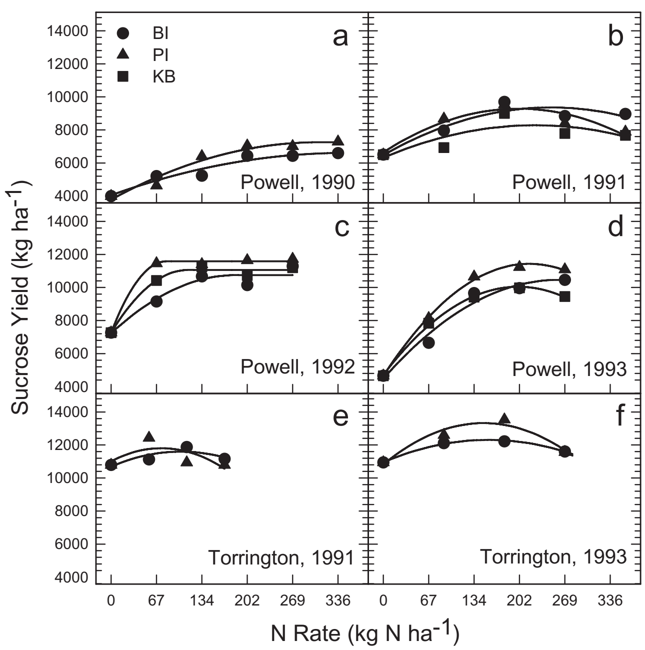

Fig. 3. Sugarbeet sucrose yield response to N fertilizer application rate and method [broadcast and incorporated (BI), point-injected (PI), or knife-banded (KB)] at (a–d) Powell and (e, f) Torrington, WY. Results from Torrington in 1992 are not included because the response to applied N was not significant for that site-year. Functions and statistics describing each response curve are presented in Table 5.

Table 5. Functions and statistical parameters describing the sugarbeet sucrose yield response to the amount of N applied with three different preplant N application methods.† Response curves are presented graphically in Fig. 3. Data are from experiments conducted at Powell and Torrington, WY. Results from Torrington in 1992 are not included because the response to applied N was not significant for that site-year.

Year	Placement	Response function	R^2	P
		Powell		
1990	BI	For N < 348, RSY = 4049 + 14.7N − 0.021N^2	0.939	0.015
		For N ≥ 348, RSY = 6611		
1990	PI	For N < 310, RSY = 3790 + 22.47N − 0.036N^2	0.956	0.009
		For N ≥ 310, RSY = 7264		
1991	BI	RSY = 6483 + 23.2N − 0.047N^2	0.892	0.108
1991	PI	RSY = 6650 + 26.3N − 0.066N^2	0.895	0.106
1991	KB	RSY = 6318 + 17.5N − 0.039N^2	0.653	0.347
1992	BI	For N < 187, RSY = 7218 + 387N − 0.511N^2	0.936	0.064
		For N ≥ 187, RSY = 10761		
1992	PI	For N < 82, RSY = 7269 + 1067N − 0.65N^2	0.996	0.004
		For N ≥ 82, RSY = 11592		
1992	KB	For N < 114, RSY = 7269 + 66.77N − 0.361N^2	0.985	0.015
		For N ≥ 114, RSY = 11062		
1993	BI	RSY = 4484 + 46.3N − 0.090N^2	0.973	0.027
1993	PI	RSY = 4653 + 62.8N − 0.145N^2	0.998	0.002
1993	KB	RSY = 4720 + 53.3N − 0.133N^2	0.998	0.002
		Torrington		
1991	BI	RSY = 10695 + 17.4N − 0.084N^2	0.718	0.531
1991	PI	RSY = 11012 + 21.3N − 0.143N^2	0.478	0.723
1993	BI	RSY = 10959 + 17.2N − 0.055N^2	0.995	0.072
1993	PI	RSY = 10833 + 33.5N − 0.113N^2	0.939	0.248

† BI, broadcast and incorporated; KB, knife-banded; N, amount of N fertilizer applied; PI, point-injected; RSY, predicted root sucrose yield.

Table 6. Predicted maximum sucrose yield (Y_{MAX}), N rate required for maximum sucrose yield (N_Y), and N use efficiency (NUE)† for three N placement methods at Powell and Torrington, WY. Results from Torrington in 1992 are not included because the response to applied N was not significant for that site-year.

	Powell				Torrington	
Placement‡	1990	1991	1992	1993	1991	1993
	Y_{MAX}, kg ha^{-1}					
BI	6,611	9,365	10,761	10,458	11,597	12,300
PI	7,264	9,289	11,592	11,439	11,807	13,320
KB	–	8,286	11,062	10,045	–	–
	N_Y, kg ha^{-1}§					
BI	348	249	187	258	104	156
PI	310	200	82	216	75	148
KB	–	225	114	200	–	–
	NUE, kg sucrose kg^{-1} available N					
BI	16.8	28.6	39.1	30.8	38.7	48.8
PI	20.4	33.4	68.2	38.4	43.6	54.6
KB	–	27.3	54.8	35.6	–	–

† NUE = Y_{MAX}/total available N (N_Y + preplant soil N + mineralized N).
‡ BI, broadcast and incorporated; KB, knife-banded; PI, point-injected.
§ Predicted values were derived from the sucrose yield response functions in Table 5 by determining the point on the quadratic response curve where the slope is equal to zero (i.e., the first derivative with respect to x).

Y_{MAX} 1394 kg ha^{-1} lower than with PI. Averaged across site-years, PI required 45 and 14 kg ha^{-1} less N to maximize yield than did BI and KB, respectively.

While Y_{MAX} and N_Y are informative when they are considered individually, it is more useful to combine them together as a direct assessment of NUE by dividing Y_{MAX} by total available N (N_Y + preplant soil N + mineralized N). Nitrogen use efficiency ranged from 16.8 to 68.2 kg sucrose kg^{-1} available N (Table 6). In all six site-years where a response to N occurred, NUE was highest with PI. Averaged across site-years, NUE with PI and BI was 43.1 and 33.8 kg sucrose kg^{-1} available N, respectively. For two of the three site-years where KB was included, NUE with KB was intermediate between PI and BI. The three-site-year average NUE values for PI, KB, and BI were 46.7, 39.2, and 32.8 kg sucrose kg^{-1} available N, respectively.

One would expect that an increase in NUE would lead to a corresponding increase in net economic return. This benefit was demonstrated by Van Tassell et al. (1996), who quantified the economic benefits of PI based on data from the Powell site of this study. In spite of considerable equipment costs for the spoke-wheel injector, estimated net profits were about \$165 ha^{-1} more for PI than for BI, and \$232 ha^{-1} more than for KB.

The difference between PI and KB in this study is probably not a function of the equipment itself, but is likely a function of the fertilizer placement position relative to the plant row. Nitrogen applied close to the row may be expected to be more available to the young plant and stimulate more rapid leaf-area development. Yield potential is strongly influenced by early leaf-area development, which in turn is affected by available-N concentration in the seedling root zone (Milford et al., 1985a, 1985b). Broadcast applications must be applied at higher rates to produce the necessary N concentration in the seedling root zone. Knife-banded applications in this study were applied further from the row than PI applications because of the greater potential for KB to disturb the seed row. Knife banding provides a high N concentration at a relatively low application rate, but the sugarbeet seedlings were likely N deficient until the root system developed sufficiently to absorb N from the band located 18 cm from the seed row. Such a deficiency could persist for weeks with sugarbeet because its tap root grows primarily in a downward direction with little lateral root development until more than 2 mo following emergence (Weaver, 1926). This effect was illustrated by Anderson and Peterson (1978), who reported that ^{32}P placed 5 cm directly under a sugarbeet row was absorbed more effectively by sugarbeet seedlings than was ^{32}P placed 5 cm below and 5 cm to the side of the seed row.

It is reasonable to expect that differences in fertilizer placement with BI, PI, and KB also influence N leaching differently, especially when preemergence irrigation is practiced, as is the case in Wyoming's Bighorn Basin. Postharvest soil profile sampling at Powell has shown that with preplant broadcast application of N, profile NO_3–N concentrations following sugarbeet are similar regardless of the amount of N applied (J. Lauer, 1990, unpublished data), indicating that substantial leaching of fertilizer N occurs. Researchers at other locations have also shown that when preplant broadcast N application is combined with early season furrow irrigation, the potential for N leaching is elevated (Meek et al., 1995; Robbins and Carter, 1980).

With banded applications, the location of the fertilizer in relation to the furrow bottom has been shown to impact N movement in ridge-till corn production. Jaynes and Swan (1999) evaluated the effect of band position relative to the ridge top on the movement of anionic solutes under rainfed conditions. Solute movement decreased as band position was moved from the furrow bottom to the ridge shoulder to the ridge top. Waddell and Weil (2006) concluded that N placed in the ridge was more efficiently utilized by corn than N placed in the furrow bottom. The same principle applies to furrow-irrigated systems. Lysimeter (Kemper et al., 1975) and simulation data (Benjamin et al., 1994) suggest that less solute will be leached when fertilizer is banded within the ridge above the water level than when broadcast or placed in the furrow bottom. For the fertilizer band to be above water level, it is also likely to be positioned close to the plant roots, which is particularly beneficial for sugarbeet given the nature of its root growth and development.

Results from these studies support our hypothesis that the improved NUE we observed with PI was due to reduced leaching of preplant N and a more favorable juxtaposition of the fertilizer band in relation to the seedling root. This advantage should be greatest when the seedling root zone is low in plant-available N. Lower spring soil NO_3–N levels and greater N leaching due to the pregermination irrigation at Powell likely contributed to a more N-depleted environment for sugarbeet seedlings than at Torrington, causing sugarbeet at Powell to exhibit a clearer response to N placement (Table 3). One factor in the limited response observed at the Torrington location was the presence of substantial amounts of residual N in the lower portion of the root zone. This underscores the importance of including deep soil NO_3–N in N recommendation algorithms for deep-rooted crops such as sugarbeet.

CONCLUSIONS

The findings of this study agree with those of previous research in support of the hypothesis that precision placement of N in close proximity to the seed row increases NUE by enhancing early N uptake and reducing the potential for N leaching. We conclude that (i) preplant PI application enhances sugarbeet root yield while having little effect on root sucrose content; and (ii) placement of preplant fertilizer N in close proximity to the seed row improves NUE because N is more readily accessible for early uptake when sugarbeet yield is being determined and is less susceptible to leaching compared with broadcast application. Of the three application methods evaluated in this study, PI generally resulted in the highest yield and NUE. Knife-banding also improved NUE compared with BI, but resulted in lower overall root and sucrose yield because the fertilizer band was placed further from the seed row.

This study demonstrates the advantages of precision N placement in a furrow-irrigated system. A producer can apply N in any number of ways, but the spoke-wheel injector increases the options for in-row applications. Results show that PI in furrow-irrigated sugarbeet can improve productivity, NUE and grower profits by providing a means for more efficient N application. The benefit will be even greater in areas where there are penalties for associated with the environmental impact of N loss.

These results reflect only preplant N applications, but it is reasonable to expect that benefits to precision placement will be observed with postemergence applications as well. It is likely that NUE and productivity would be further enhanced with a split application using precision placement methods for both preplant and postemergence applications, especially where early season furrow irrigation is practiced. This approach would provide a portion of the fertilizer N during seedling development while the remainder is applied just before the midseason rapid uptake period.

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